

# Measurement of non-axisymmetry in centres of advanced mergers of galaxies

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## ABSTRACT

We measure the non-axisymmetry in the luminosity distribution in the inner few kpc of the remnants of advanced mergers of galaxies with a view to understand the relaxation in the central regions. For this, we analyze the images from the Two Micron All Sky Survey (2MASS) archival data for a selected sample of 12 merging galaxies, which show signs of interaction but have a single nucleus. The central regions are fitted by elliptical isophotes whose centres are allowed to vary to get the best fit. The centres of isophotes show a striking sloshing pattern with a spatial variation of up to 20-30 % within the central 1 kpc. This indicates mass asymmetry and a dynamically unrelaxed behaviour in the central region. Next, we Fourier-analyze the galaxy images while keeping the centre constant and measure the deviation from axisymmetry in terms of the fractional Fourier amplitudes ( $A_1$ ,  $A_2$  etc) as a function of radius. All the mergers show a high value of lopsidedness (upto  $A_1 \sim 0.2$ ) in the central 5 kpc. The  $m=2$  asymmetry is even stronger, with values of  $A_2$  upto  $\sim 0.3$ , and in three cases these are shown to represent bars. The corresponding values denoting non-axisymmetry in inner regions of a control sample of eight non-merger galaxies are found to be several times smaller.

Surprisingly, this central asymmetry is seen even in mergers where the outer regions have relaxed into a smooth elliptical-like  $r^{1/4}$  profile or a spiral-like exponential profile. Thus the central asymmetry is long-lived, estimated to be  $\sim 1$  Gyr, and hence lasts for over 100 local dynamical timescales. These central asymmetries are expected to play a key role in the future dynamical evolution of the central region of a merger, and can help in feeding of a central AGN.

**Key words:** Galaxies: evolution - Galaxies: kinematics and dynamics - Galaxies: interactions - Galaxies: photometry- Galaxies: structure

## 1 INTRODUCTION

Interactions and mergers of galaxies are now known to be common and these can significantly affect the dynamics and evolution of the merging galaxies (Wielen 1990, Barnes & Sanders 1999). The work so far has mainly concentrated on the intermediate radial range of a few kpc - few  $\times 10$  kpc : observationally, the mergers have been shown to result in an elliptical-like  $r^{1/4}$  profile as was first shown for NGC 7252 by Schweizer (1982), and later by others for larger samples (Wright et al. 1990, Stanford & Bushouse 1991, Chitre & Jog 2002). Interestingly, in half the sample of mergers showing

a single nucleus but evidence for tidal interaction as studied by Chitre & Jog (2002), the remnants even showed an exponential profile like a disc while a few showed no-fit implying unrelaxed outer regions. The galaxies with disc-like profiles are peculiar and have elliptical-like high velocity dispersion and could have thick discs, as shown for two galaxies (Jog & Chitre 2002). Theoretically the evolution of mergers leading to a relaxed elliptical-like remnant has been well-studied by N-body simulations (e.g., Barnes 1992, Bournaud et al. 2005 b). Recent simulations of unequal-mass mergers can reproduce the above, relaxed disc-like remnants (Bournaud et al. 2004, Naab & Trujillo 2005), while the transition between the elliptical-like and spiral-like remnants is shown to occur for a narrow mass-range of 3:1-4.5:1 (Bournaud et al. 2005 b). An inclusion of gas has also shown to result in a disc-like remnant in some cases (Volker & Hernquist 2005).

However despite its obvious importance for the evolu-

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tion of the central regions, the luminosity distribution in the central regions of mergers has not been studied systematically so far. A few mergers where this has been studied, such as NGC 3921 (Schweizer 1996), and Arp 163 (Chitre & Jog 2002), show a wandering or meandering centre for the isophotes. But there has been no study so far to measure the non-axisymmetric amplitudes in mergers.

In this paper, we systematically study the asymmetry in the central few kpc of advanced mergers of galaxies. The recent availability of near-IR data (including the excellent archival 2MASS database) allows one to study the main underlying mass distribution directly in the central regions of mergers for a large sample of galaxies. In the near-IR, the dust extinction is low and the luminosity distribution directly traces the old stellar component, and hence the main mass component.

The mergers involve a patently non-axisymmetric configuration, especially at large radii (of 20-30 kpc) outside of the main merged body where spectacular tidal features are seen. Even the inner optical image is patchy, especially as seen in the blue light where the dust obscuration plays a major role. Hence, naively it would seem that they would show asymmetry in the central regions of few kpc as well. However, the advanced mergers do show some degree of relaxation as evident from their merged centres, and their relaxed outer profiles ( $\sim 10$  kpc or so), as seen in the near-IR, as discussed above. Further, the dynamical timescales are smaller in the inner regions and hence they would be expected to be more relaxed than the outer parts. Thus it is interesting to measure the values of non-axisymmetry in the central regions of mergers. For example, the values of central lopsidedness can provide an important diagnostic for the degree of relaxation in the central regions of a merging pair of galaxies.

Our earlier study of Arp 163 (Chitre & Jog 2002) showed a wandering centre. This is a no-fit merger - which cannot be fit by an elliptical or an exponential fit, where the outer regions are not relaxed. In this paper, we measure the central asymmetry in the mergers with no-fit in the outer regions as well as in the other mergers which show relaxed outer profiles. Thus this study is expected to provide information on the relaxation in the inner regions, and also reveal the correlation if any of the central asymmetry or degree of relaxation with that in the outer regions.

We do a detailed isophotal analysis of the galaxy images and study the sloshing of the isophotal centres quantitatively, and then Fourier analyze the images and obtain the amplitudes for lopsidedness and also for  $m=2$ . In three cases the latter are shown to represent a strong bar.

We show that the lopsidedness is high in all cases, and the magnitude of the central asymmetry is higher in those mergers which are unrelaxed in the outer regions. Interestingly, even galaxies where the outer regions have relaxed into a smooth mass profile still display a fairly strong central asymmetry and hence a non-relaxed central mass distribution.

Section 2 contains a discussion about the sample selection, and the basic properties of the sample galaxies. Section 3 contains data analysis and the results for mergers, and a comparison with results for a set of non-merger or normal galaxies. Section 4 includes a discussion of the dynamical

implications of the results, and a brief summary is given in Section 5.

## 2 SAMPLE SELECTION

The sample galaxies were chosen to be advanced mergers of galaxies which have already lost their identities and merged into a single nucleus (up to the resolution limit of 2" in 2MASS), and which still looked disturbed and had signs of recent interaction like tidal tails, plumes etc, for more details see Chitre & Jog (2002). The galaxies were chosen from the Atlas of peculiar galaxies (Arp 1966) and the Arp-Madore catalogue of southern peculiar galaxies (Arp & Madore 1987).

Our earlier work (Chitre & Jog 2002) showed that these could be divided into three dynamically distinct classes: where the luminosity profiles could either be fitted by an  $r^{1/4}$  profile (class I), or an outer exponential (class II), or a no-fit (class III). In the present paper, we have chosen representative examples from each of these classes, with an emphasis on class III which showed sloshing of the inner isophotes even on a visual inspection (Chitre & Jog 2002). Of that sample of 27 galaxies, only those galaxies which had a large enough angular size for non-axisymmetric analysis were chosen. This meant that they should be divisible into at least 5-6 annular rings, with each ring size about twice the resolution of the 2MASS data, so that a meaningful non-axisymmetric analysis could be carried out. The J-band data was used for this purpose for all the galaxies since the images are deeper in this band allowing for a radial sampling.

This led to a total of eight galaxies to be selected. To this, we added a further four more galaxies from the Arp and Arp-Madore catalogs for which such a non-axisymmetric analysis could be carried out, to supplement our sample: namely, Arp 209, Arp 254, AM 1025-433, and AM 0612-373.

Thus, the total sample used for the present work consists of 12 galaxies divided into the three classes as follows:  
 Class I : Arp 221, Arp 222, Arp 225, AM 0612-373  
 Class II: Arp 162, Arp 212, Arp 224  
 Class III: Arp 160, Arp 163, Arp 209, Arp 254, AM 1025-433.

The four new galaxies chosen here which were not in our earlier sample fall into class I (AM 0612-373) and class III (Arp 209, Arp 254, AM 1025-433): the luminosity profiles defining the classification of all the galaxies are given below.

For the radial fits, and the isophotal analysis we used the  $K_s$ -band data for all galaxies. This is because the dust extinction effects are least important for this band (than say J or H) and hence this is suitable for the central sloshing to be studied via the isophotal analysis.

The 2MASS full-resolution images for extended sources were obtained from the 3-dimensional FITS image cubes or from the mosaic images for larger galaxies. The  $K_s$  band images were analysed using the task ELLIPSE within STSDAS<sup>‡</sup>. The procedure consisted of fitting elliptical

<sup>‡</sup> STSDAS is a product of the Space Telescope Science Institute, which is operated by AURA for NASA.

**Table 1.** Basic data on mergers of galaxies

Name	Alt. name	$R_e, R_D$ (kpc)	velocity (km s $^{-1}$ )	1'' $^a$ (pc)
Class I				
Arp 221	-	5.76±0.41	5546	358
Arp 222	NGC 7727	2.83±0.46	1855	125
Arp 225	NGC 2655	3.26±0.38	1404	91
AM 0612-373	-	11.26±0.45	9864	620
Class II				
Arp 162	NGC 3414	1.56±0.04	1414	87
Arp 212	NGC 7625	0.85±0.03	1633	104
Arp 224	NGC 3921	2.91±0.21	5838	383
Class III				
Arp 160	NGC 4194	-	2442	168
Arp 163	NGC 4670	-	1069	78
Arp 209	NGC 6052	-	4716	305
Arp 254	NGC 5917	-	1904	123
AM 1025-433	NGC 3256	-	2814	182

$a$  Using  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$

isophotes to the galaxy images and deriving the one-dimensional azimuthally averaged radial profiles for the surface brightness, ellipticity, position angle, etc. based on the algorithm given by Jędrzejewski (1987). The centre, position angle and ellipticity were allowed to vary. Ellipses were fit right up to the central pixel. The parameters thus derived, namely the surface brightness profile, the ellipticity and the position angle variation, and  $x_0, y_0$  -the x and y coordinates of the centres, were studied.

The resulting surface brightness radial profiles are plotted for all the 12 sample galaxies in Figure 1. The luminosity profile-fitting for eight of these galaxies from our earlier sample has already been done (see Fig.1 in Chitre & Jog 2002). As discussed in that paper, surprisingly, the profiles can be best fit by an outer exponential in four cases; and the fit is robust in the sense that the radial range over which the fit is valid is typically 2 times the disc scalelength or larger, and the error bars are small. The values of the de Vaucouleurs scalelength,  $R_e$  (for class I galaxies), and the exponential disc scalelength,  $R_D$  (for class II galaxies) are given in Table 1. This figure defines the classification for the four new galaxies as follows: AM 0612-373 (class I), Arp 209, Arp 254, and AM 1025-433 (class III).

The Table 1 lists the sample chosen, distributed in terms of this classification, with all the relevant astronomical parameters (Galaxy name, Alternate name,  $R_e, R_D$ , velocity, and 1'' in pc) for the three classes showing the different radial fits.

### 3 DATA ANALYSIS AND RESULTS

#### 3.1 Isophotal Analysis: Sloshing

The isophotal analysis of the images is carried out as described in the last section. The centre, position angle and ellipticity were allowed to vary to obtain the best fit by ellipses to the galaxy image.

In Figure 2, we plot a block of 4 diagrams for each galaxy, which shows the centres of the isophotes ( $x_0, y_0$  vs.

**Table 2.** Average central asymmetry properties for mergers

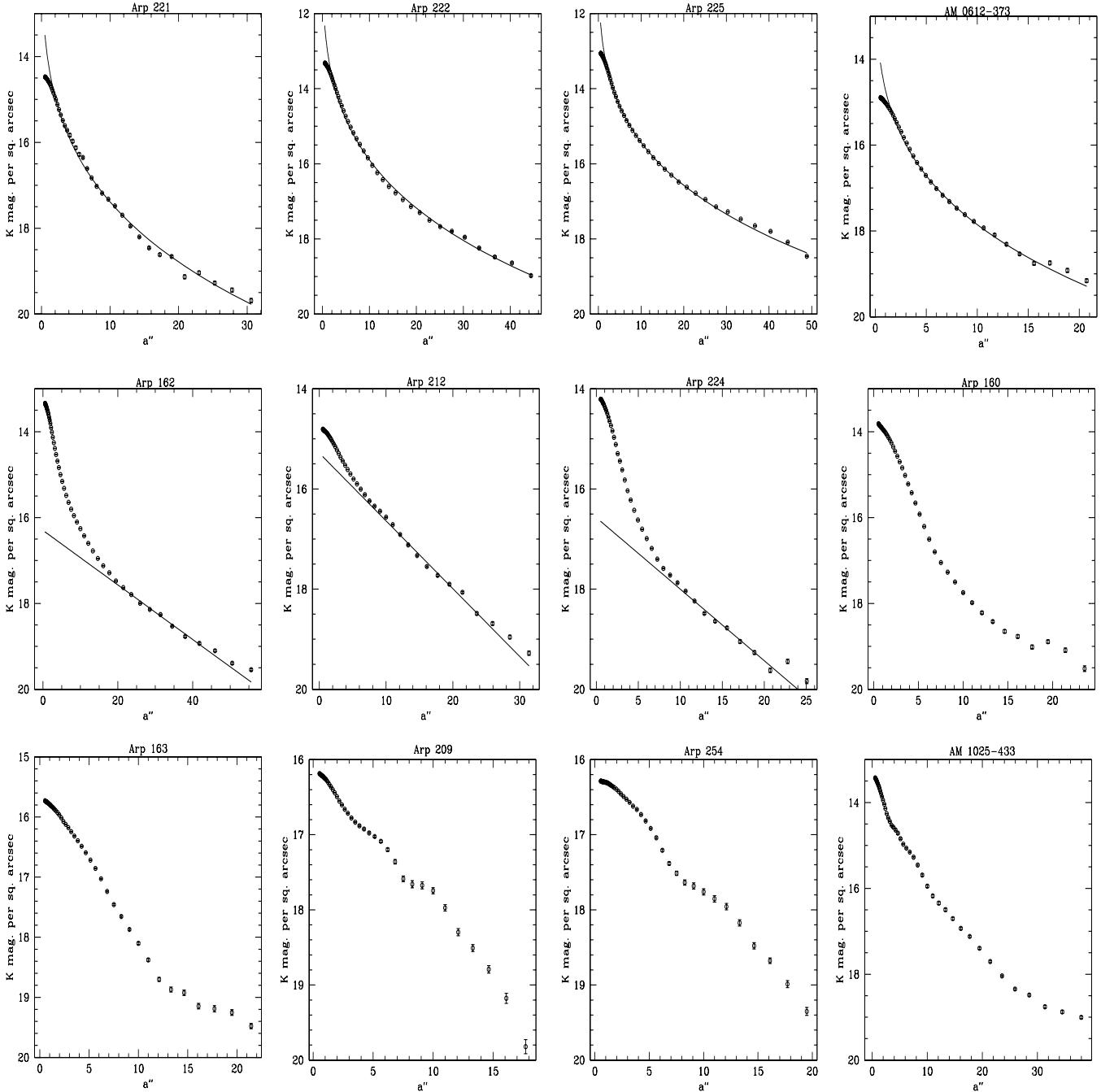
Name	Sloshing of centre within 1 kpc	$\langle A_1 \rangle$ within 5 kpc	$\langle A_2 \rangle$ within 5 kpc
Class I			
Arp 221	0.08	0.16	0.09
Arp 222	0.10	0.04	0.18
Arp 225	0.09	0.03	0.29
AM 0612-373	0.10	0.05	0.17
<b>Avg.: Class I</b>	0.09	0.07	0.18
Class II			
Arp 162	0.06	0.02	0.24
Arp 212	0.08	0.11	0.19
Arp 224	0.14	0.23	0.16
<b>Avg.: Class II</b>	0.09	0.12	0.20
Class III			
Arp 160	0.27	0.15	0.30
Arp 163	0.31	0.15	0.19
Arp 209	0.04	0.23	0.22
Arp 254	0.06	0.09	0.34
AM 1025-433	0.20	0.16	0.29
<b>Avg.: Class III</b>	0.18	0.16	0.27

$a$ , the semi-major axis of the elliptical isophote (in units of kpc). Also shown are the ellipticity and the position angles (PA) versus  $a$ , the semi-major axis. Clearly, in most cases, the centres of the isophotes do not remain constant. Instead, they show a wandering or a sloshing behaviour. *This indicates a dynamically unrelaxed central mass distribution.* In general, the sloshing is higher in the class III galaxies which are also unrelaxed in the outer regions. This is confirmed by a quantitative measurement of normalized sloshing within  $a = 1$  kpc, which is given as average of  $((x - x_0)^2 + (y - y_0)^2)^{1/2}/a$  - see Table 2. This allows a comparison of sloshing seen in the various classes of galaxies.

#### 3.2 Non-axisymmetry: Fourier Amplitudes

The images from 2MASS of mergers were Fourier-analyzed to obtain the amplitudes and phases of the Fourier components  $m = 1, 2, 3$  and 4, measured w.r.t. a constant centre. A similar approach has been used in the past to divide the near-IR images of normal galaxies into radial bins, and measure the deviation from axisymmetry in terms of the fractional Fourier amplitudes such as  $A_1$  and  $A_2$  measured w.r.t.  $A_0$  the average amplitude, where  $A_1$  denotes the amplitude for lopsidedness ( $m=1$ ) and  $A_2$  denotes the amplitude for bars or disk ellipticity or spirals (e.g., Rix & Zaritsky 1995, Laurikainen et al. 2003, Buta et al. 2005).

In our analysis, the centre is kept constant and the Fourier analysis is carried out over annular rings w.r.t. this centre. For this, we sum up the pixel values in the radial bins so that the complete 2-D data is used and we do not try to fit a curve. This procedure is similar to the one used by Rix & Zaritsky (1995). The resulting  $A_1$  and  $A_2$  amplitudes for  $m=1$  and 2 are better indicators of mass asymmetry measured w.r.t. the constant centre (than the usual boxiness etc for an isophote), especially since the centres of isophotes show a lot of sloshing in the case of mergers. For example, it is easy to see that if we use the standard isophotal analysis, then the azimuthal average taken over an isophotal contour



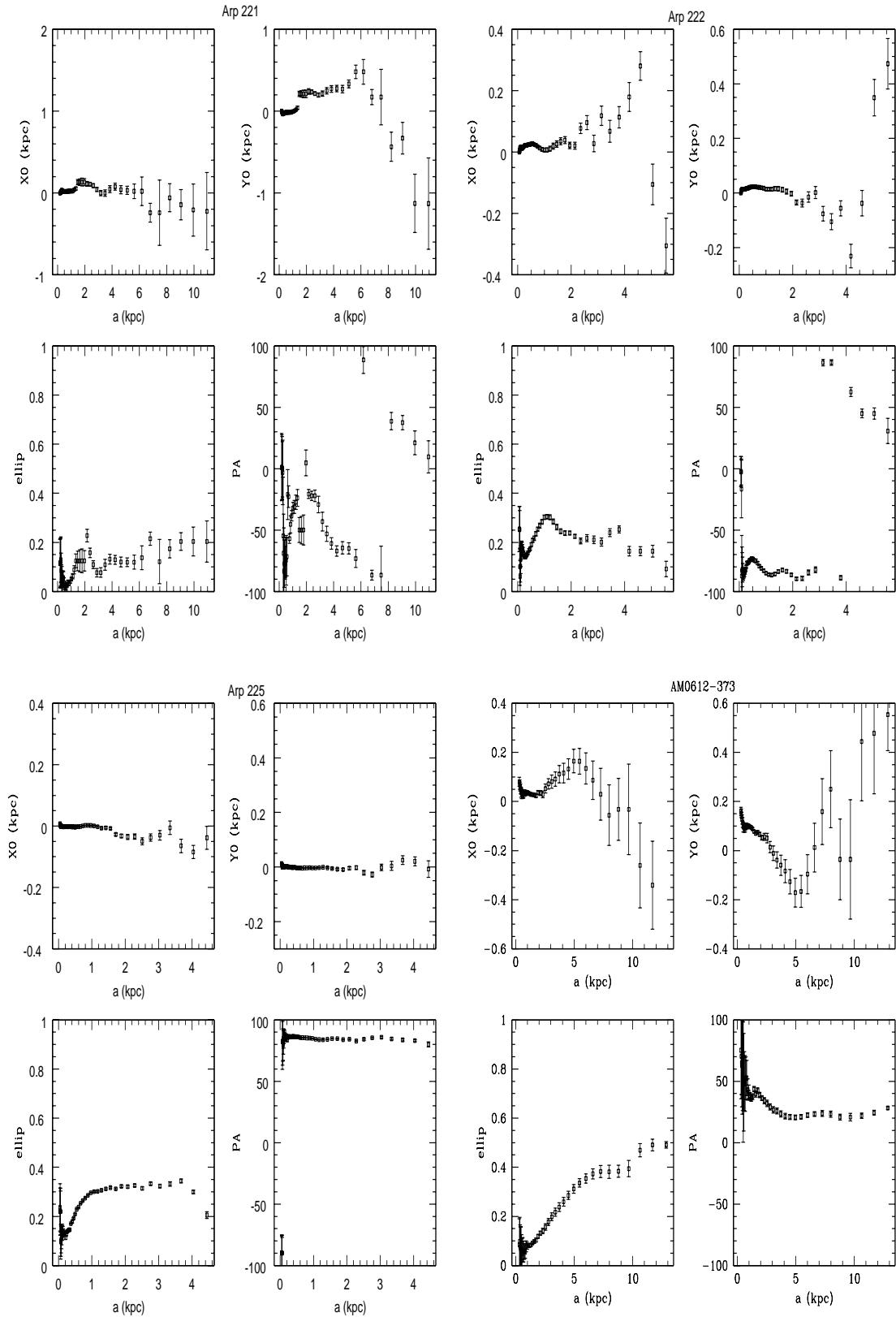
**Figure 1.** The  $K_s$ -band magnitude in  $\text{mag arc sec}^{-2}$  is plotted against the semi-major axis,  $a''$  in arc sec. The first four galaxies (Arp 221, Arp 222, Arp 225, and AM 0612-373) are well fit by an  $r^{1/4}$  law (class I); the next three (Arp 162, Arp 212, and Arp 224) are well fit by an outer exponential (class II), and the last five are no-fit galaxies (class III).

w.r.t. the isophotal centre would give a zero average lopsidedness since the average of  $\cos \phi$  would be zero.

Thus, for measuring the non-axisymmetric mass distribution we need to keep the centre constant and then measure the Fourier amplitudes over annular radial bins, for this a special procedure was adopted which is described below.

First, the x and y co-ordinates of the centre of the galaxy (or the stellar centre) were determined using the task "imexam" in IRAF and plotting the radial profile. Once this pixel value was found in terms of the x and y co-ordinates

of the frame, we designated the rest of the image pixels in terms of the distance  $r$  and the angle  $\theta$  from the centre. The image was then cut into annular regions. A polar coordinate grid was centered on the galaxy nucleus with 36 azimuthal bins with 10 degrees per bin, and the number of radial bins depended on the size of the galaxy. In each case, we took the radial width of the annular ring to be at least 2 times the resolution of the image. The pixel intensity values in each bin were summed to give an average value per bin. Using the



**Figure 2.** Plots of isophotal analysis for the  $K_s$ -band data for the sample galaxies. For each case, we plot a block of 4 plots, showing the centre  $x_0, y_0$  vs the semi-major axis  $a$  of the fitted isophotes, and also the ellipticity and the position angle (PA) versus  $a$ . All the galaxies on this page are class I galaxies.

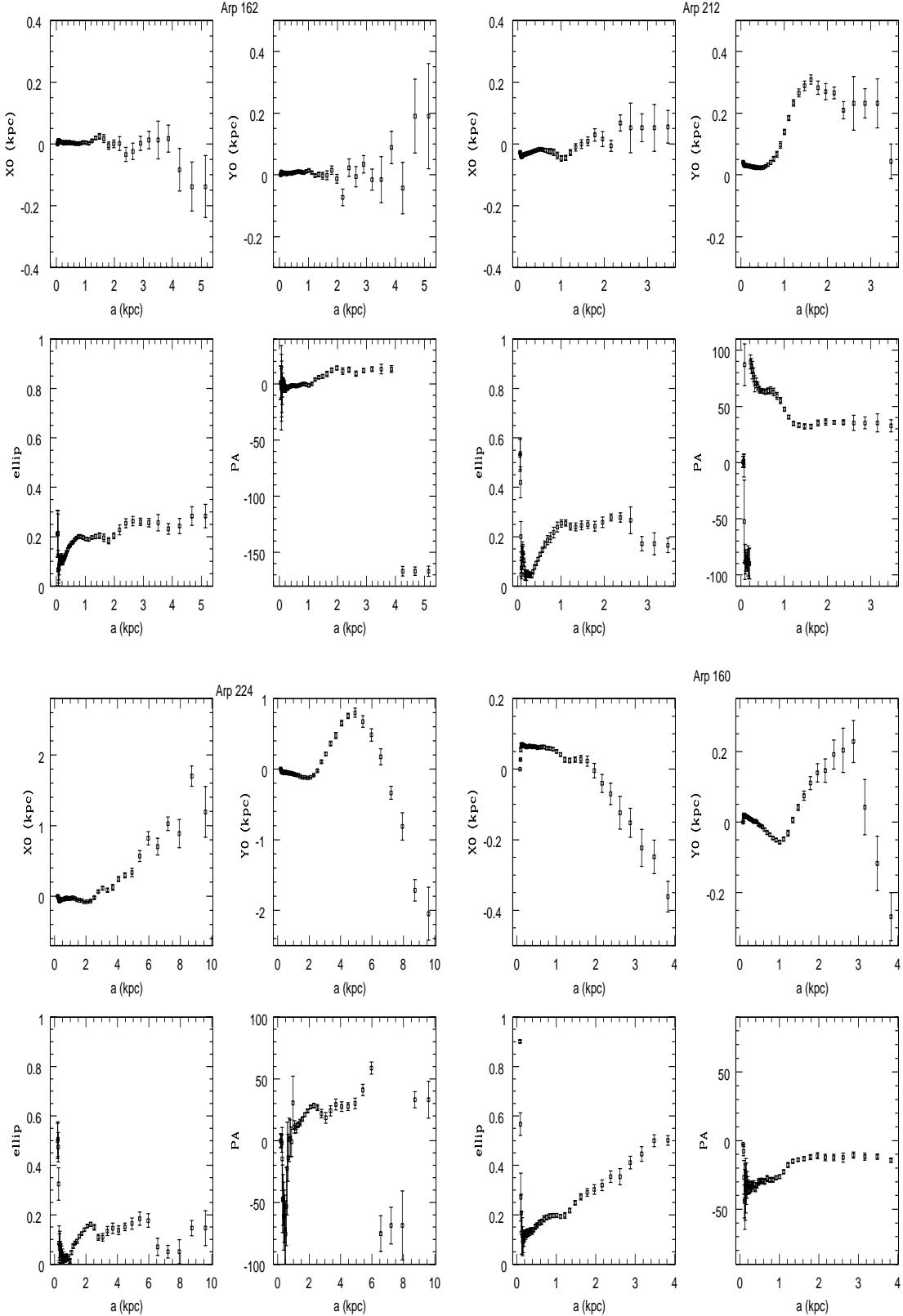


Fig 2(contd.)

Arp 162, Arp 212, and Arp 224 are class II type galaxies, while Arp 160 is a class III type galaxy- it shows a larger sloshing of the centre ( $x_0, y_0$ ) of isophotes.

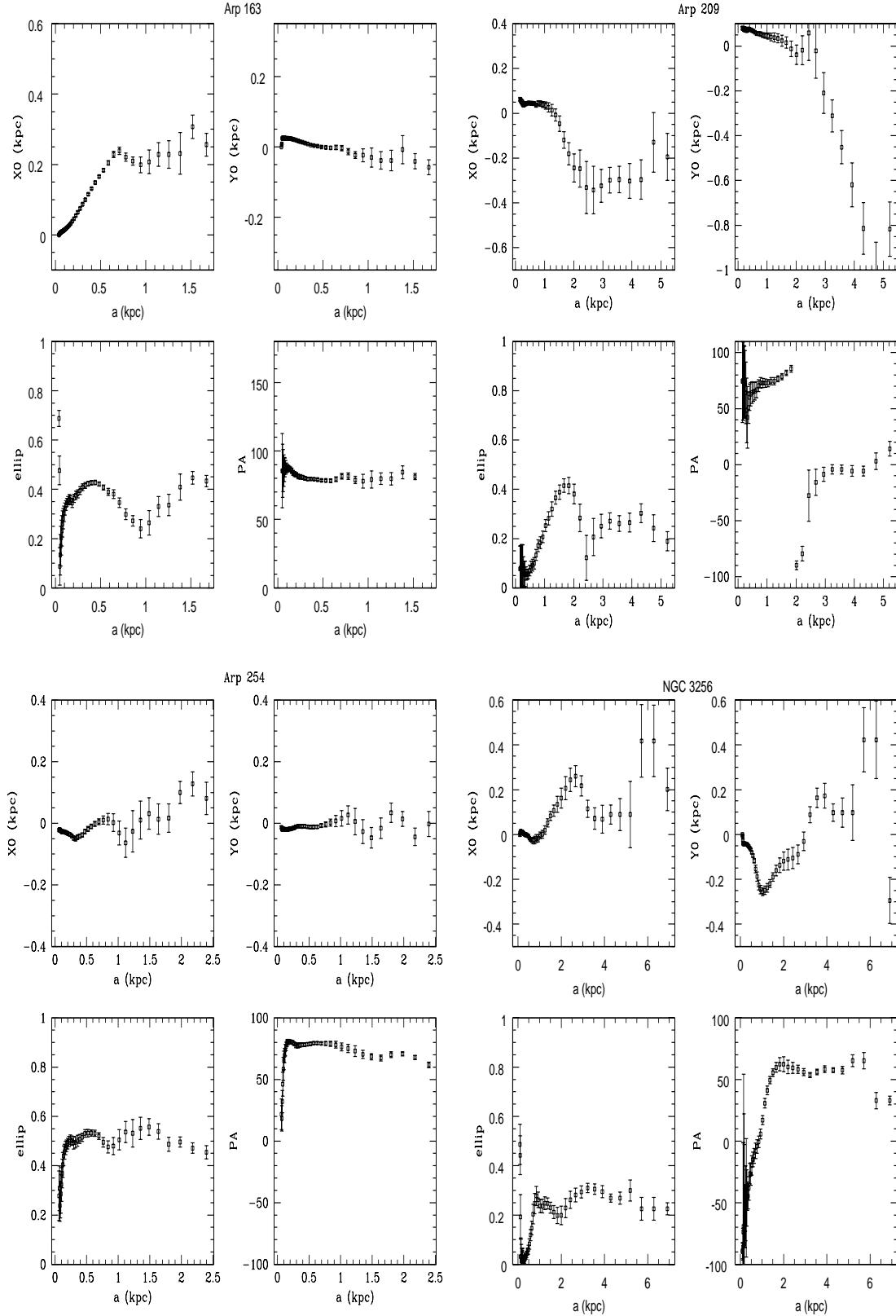


Fig 2(contd.)

All the galaxies shown are class III type- and they show larger sloshing than shown by Class I or II.

task "nfit1d" within STSDAS, we fit the following function,  $f$  to each annular region:

$$f = A_0 + A_0 * [A_1 * \cos(x - p_1) + A_2 * \cos(2x - 2 \times p_2) + A_3 * \cos(3x - 3 \times p_3) + A_4 * \cos(4x - 4 \times p_4)] \quad (1)$$

where the  $A_1, A_2$  etc denote the fractional Fourier amplitudes and the  $p_1, p_2$  etc denote the phases of the various Fourier components. Each annular region in the image gives one set of values for the above fitting. The number of points we get in the final plot are the same as the number of annular regions that were made in the original image.

In Figure 3, we plot the fractional amplitudes  $A_1, A_2$  and the phases  $p_1, p_2$  versus radius  $r$  (in '') for  $m=1$  and  $2$  respectively. The  $m=3$  and  $4$  amplitudes are generally smaller, and  $m=3$  is important only when  $m=1$  is large. For the sake of brevity, we do not show the amplitudes and phases for  $m=3$  and  $4$  for the sample. However, in the notes on individual galaxies (Appendix A) we also add comments about  $A_3$  and  $A_4$  when relevant.

Figure 3 shows that all the mergers studied show a high value of lopsidedness ( $A_1$ ), the values are generally higher for the class III galaxies - see Table 2 for the detailed values including the averages over the classes. The average values for  $A_1$  and  $A_2$  are given over the central 5 kpc in each merger since it represents a typical central region, and also this allows a comparison between different galaxies.

In order to avoid any spurious variation with class introduced due to the dependence on the band chosen, we have taken homogeneous data (in J-band from 2MASS) for all the galaxies for the above non-axisymmetric analysis (Fig. 3), and the  $K_s$ -band data from 2MASS for the isophotal analysis (Fig. 2).

Figure 3 shows that the values of  $A_2$  in mergers are also large. Normally, the values of  $A_2$  are taken to denote bars or spirals or disc ellipticity (Rix & Zaritsky 1995, Buta et al. 2005, Bournaud et al. 2005 a). It is hard to see how spiral features can survive the strong disturbance in a merger. We add the evidence from the isophotal analysis and find that the characteristic feature of bars, namely increasing ellipticity and a nearly constant position angle (PA) (e.g. Wozniak et al. 1995) is seen in only three cases, which we conclude have well-defined bars. These are: Arp 160, Arp 162, and Arp 163.

Grosbol et al. (2004) state that a circular disc will appear elliptical when projected and this could give rise to an artificial bisymmetric component with a constant phase. This could be used to explain the high values of  $A_2$  seen in many galaxies in our sample. In fact this effect is seen in all the galaxies except Arp 221 (Class I), Arp 212 (Class II), and Arp 209 (Class III). Thus, in most cases studied, the merger remnants seem to indicate a preferred disc plane. This is seen even in three of the class I galaxies with an outer elliptical-like profile (Arp 222, Arp 225, AM0612-373), which is unexpected.

We note, however, that the previous work on deriving the Fourier coefficients to get the asymmetry has been done for spiral galaxies. These galaxies were deprojected by estimating their inclinations assuming that the discs are intrinsically round. It is reasonable to talk about projection effects in the case of spirals and also comparatively easy to

**Table 3.** Basic data on normal galaxies

Name	Alt. name	$R_D''^a$ (kpc)
NGC 628	M74	$2.51 \pm 0.13$
NGC 3147	-	$3.82 \pm 0.09$
NGC 4254	M100	$9.48 \pm 0.75$
NGC 4321	M99	$3.81 \pm 0.27$
NGC 4540	-	$1.37 \pm 0.04$
NGC 4689	-	$4.39 \pm 0.32$
NGC 5248	-	$7.34 \pm 1.79$
NGC 5377	-	$3.70 \pm 0.21$

<sup>a</sup> Using  $H_0 = 75 \text{ kms}^{-1} \text{Mpc}^{-1}$

**Table 4.** Average central asymmetry for normal galaxies

Name	Sloshing of centre within 1 kpc	$\langle A1 \rangle$ within 5 kpc	$\langle A2 \rangle$ within 5 kpc
NGC 628	0.07	0.04	0.10
NGC 3147	0.07	0.03	0.08
NGC 4254	0.09	0.02	0.14
NGC 4321	0.02	0.03	0.15
NGC 4540	0.13	0.10	0.15
NGC 4689	0.10	0.06	0.10
NGC 5248	0.06	0.07	0.34
NGC 5377	0.04	0.02	0.53
<b>Average:</b>	0.07	0.04	0.20

deproject these galaxies. However, here we are looking at systems completely or partially distorted by the interaction or a merger and hence it is not possible to estimate the inclination of the disc component and correct for inclination effects. A further discussion on the variation of Fourier amplitudes with class types in our sample is given in Section 4.2.

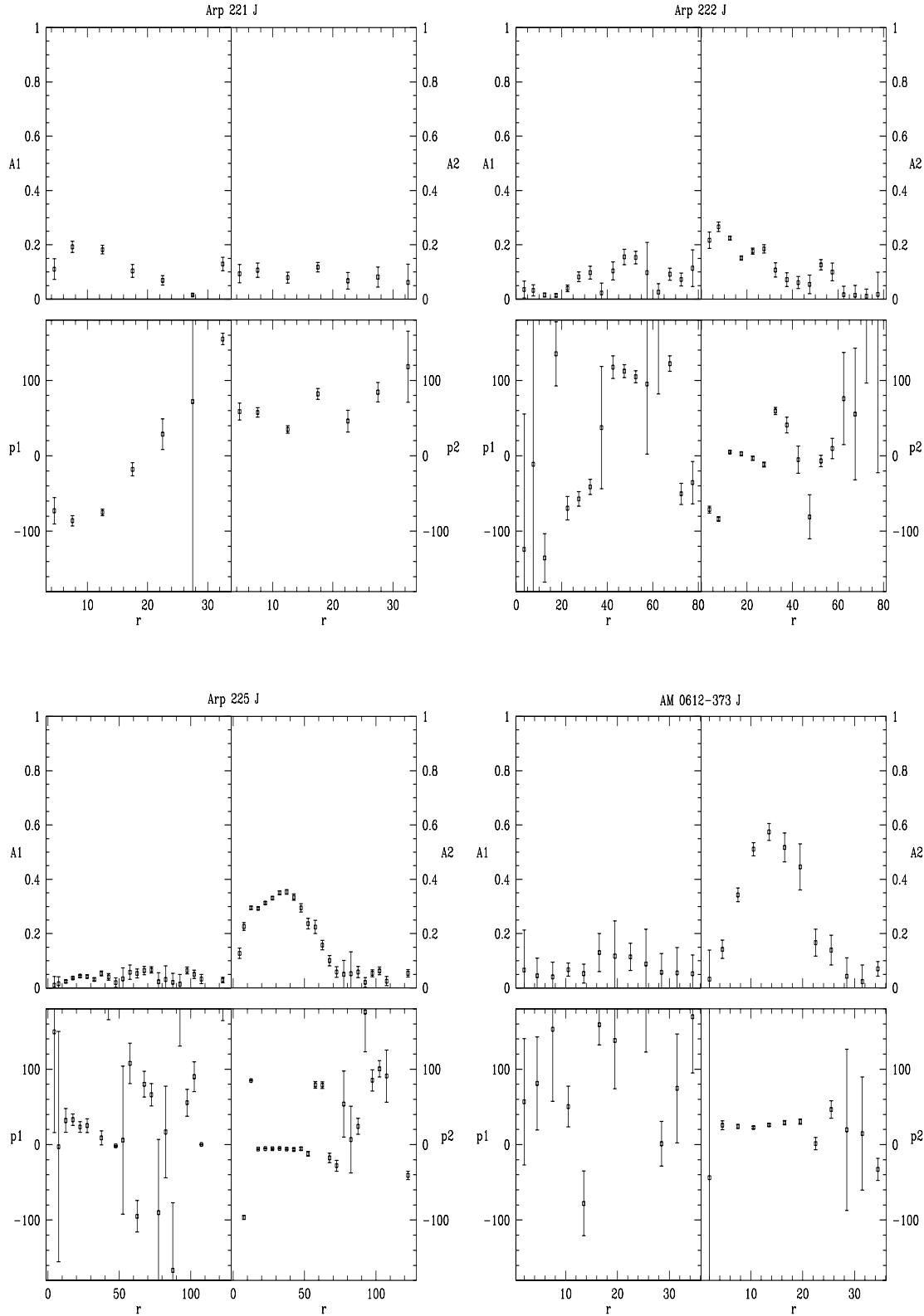
### 3.3 Comparison with non-merger galaxies

So far we have studied the mergers and we have shown these to have significant central non-axisymmetry. In order to check that the origin of this is related to the merger history, we next carry out a similar analysis for a control sample of non-merging, normal spiral galaxies and show that these indeed have lower central asymmetry.

The selection of a sample of non-merger galaxies is by no means a trivial issue. We do not include any early-type galaxies which are now believed to evolve from late-type galaxies via secular evolution or galaxy mergers. The galaxies selected are nearly face-on (for easier analysis), and are late-type and not strongly barred and not active - so as to increase the chance of their having had no interactions in the recent past. The set of eight such normal or non-merger galaxies which are also large enough in angular size to allow the non-axisymmetric analysis in J-band (see Section 2) were chosen from the 2MASS Large Galaxy Catalog (Jarrett et al. 2003), and these are: NGC 628 (M74), NGC 3147, NGC 4254 (M100), NGC 4321 (M99), NGC 4540, NGC 4689, NGC 5248, NGC 5377.

These show an outer exponential fit as expected for normal spiral galaxies. The basic data for these, including the derived disc scalelength ( $R_D$ ), is listed in Table 3.

The isophotal analysis for the  $K_s$ -band data (as in Sec-



**Figure 3.** Plots of Fourier amplitudes and phases  $A_1$  and  $P_1$  and  $A_2$  and  $P_2$  versus  $R$ , obtained from a non-axisymmetric analysis with a constant centre, for the J-band data for the entire sample studied. All mergers, especially the Class III galaxies, show a large amplitude of lopsidedness  $A_1$ .

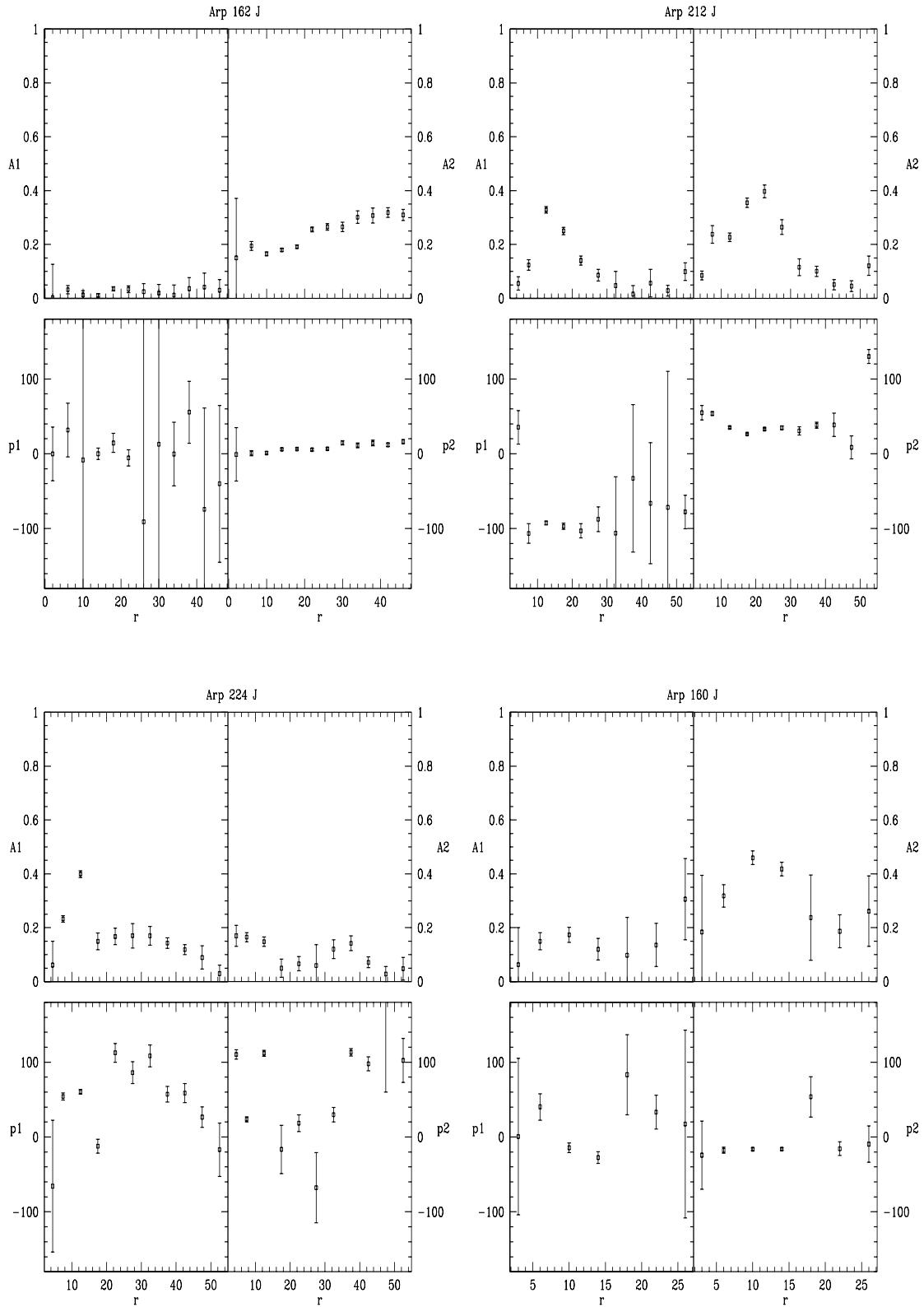


Fig 3(contd.)

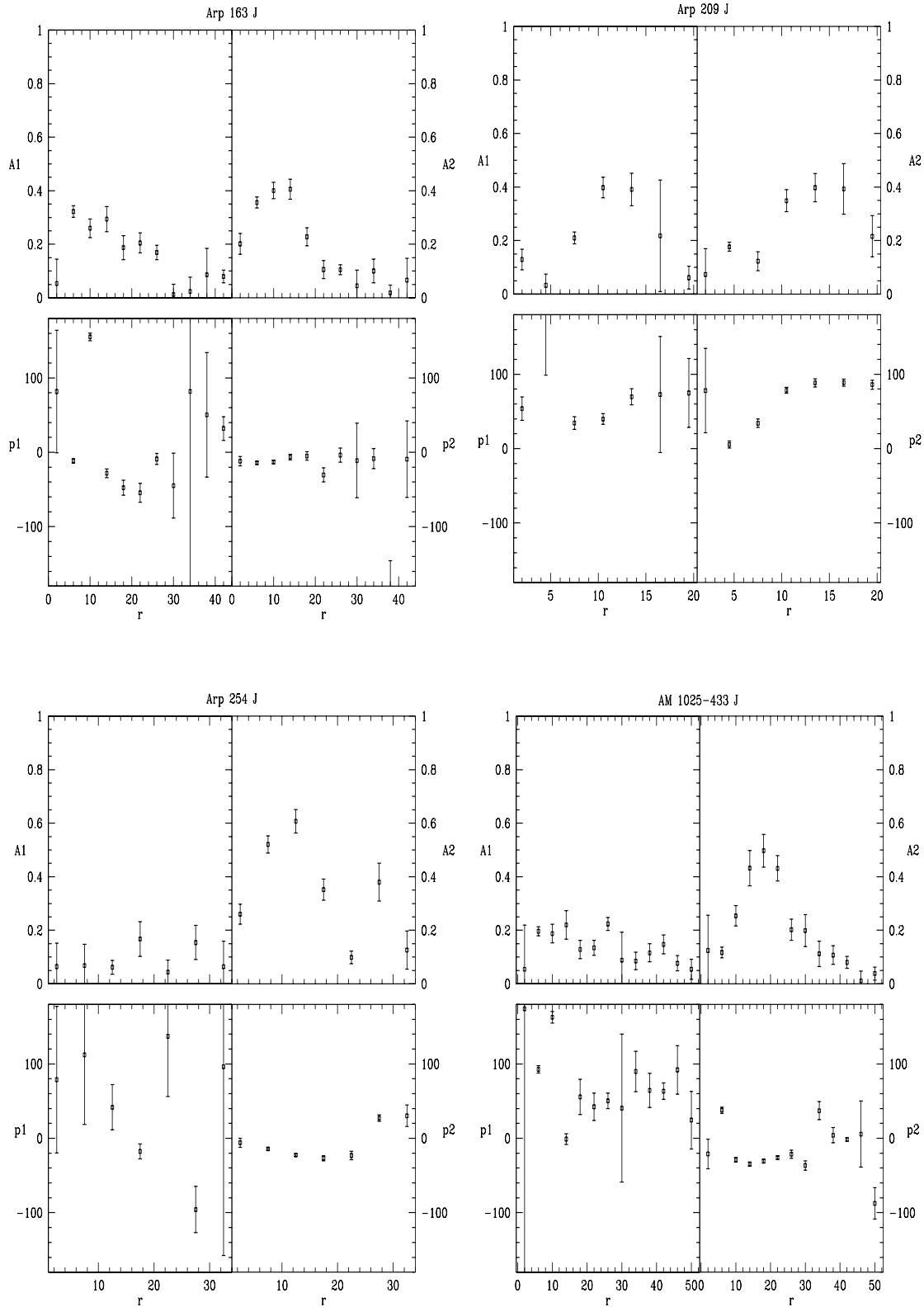


Fig 3(contd.)

tion 3.1) and the Fourier analysis for the J-band data (as in Section 3.2) were carried out for this sample. The resulting values of sloshing within 1 kpc and the mean  $A_1$  and  $A_2$  within 5 kpc are given in Table 4. We find that these show a lower magnitude for the sloshing of isophotes and a lower mean central  $A_1$  value (compare with Table 2). The non-merger or normal galaxies show sloshing values which are smaller by a factor of 2 compared to the un-relaxed (or class III) mergers. The Fourier amplitudes for lopsidedness for the normal galaxies are smaller by a factor of 2-3 compared to class I and II remnants and smaller by a factor of 4 compared to the class III remnants. Thus, the origin for the high central asymmetry (especially  $A_1$ ) observed in the merger remnants can be attributed to its merger history.

Interestingly, the mean  $A_2$  value for this sample is comparable to the class I and II galaxies, thus providing additional support for our interpretation of this (Section 3.2) as being due to an inclined disc. The higher values for  $A_2$  in the unrelaxed (class III) type galaxies then could be due to a thicker disc seen at an angle.

## 4 DYNAMICAL IMPLICATIONS

### 4.1 Long-lived Central Asymmetry:

The one clear result from this work is that all mergers show high levels of asymmetry in their central few-kpc regions, even in systems that have relaxed in the outer parts. The large sample of galaxies used here gives a statistical idea of the in-situ non-axisymmetry in merger remnants with a variety of dynamical properties. N-body simulations of unequal-mass mergers by Bournaud et al. (2004) have shown that the advanced remnants with signs of tidal interactions and disturbed profiles in the outer regions (beyond say 20 kpc or so) have ages  $\leq 2$  Gyr. Class I and II represent mergers of different mass ratios, of masses 1:1-3:1, and 4.5-10:1 respectively (Bournaud et al. 2005 b), while Class III could be younger remnants ( $\sim 1$  Gyr). The dynamical timescale in the central few kpc where the random motion are  $\sim$  a few 100 km s $^{-1}$  (e.g., Jog & Chitre 2002) is  $\sim 10^7$  yr. Thus the central regions in mergers are not relaxed in over a few hundred local dynamical timescales. This is an important and a robust dynamical result, and has important implications for the evolution of the very central regions of mergers.

For example, such asymmetries could play an important role in the fueling of the central black-hole in an AGN since they provide a means of outward transfer of angular momentum. The central asymmetries can help fuel a central black hole for a long time  $\sim 100$  dynamical timescales. Also these can be important in the gradual build-up of bulges - on lines of bars as an intermediate stage in the build-up of boxy bulges by mergers (see e.g. Walker et al. 1996).

It is instructive to compare the central lopsidedness in mergers with the lopsidedness in the outer discs of normal isolated spiral galaxies. The latter was initially believed to be short-lived ( $< 1$  Gyr) and to get wound up in a few dynamical timescales (Baldwin et al. 1980). However, more recent N-body studies of evolution of disc lopsidedness have shown that these features can be surprisingly long-lived to more than 2 Gyr or several tens of disc dynamical timescales, although the physical reason for this is still not understood

(Bournaud et al. 2005 a). The results from the present paper confirm the asymmetry in the central regions to be also long-lived and the ratio of its lifetime to the local dynamical timescales is even higher  $\sim 100$ .

It should be noted that central regions of normal galaxies like our Galaxy, M 31 and M 33 also show sloshing (Miller & Smith 1992, also see Section 3.2) where the centre is off-set with respect to the outer isophotes but the other isophotes are concentric and the off-set is believed to be due to overstability, whereas in the mergers we have studied, the isophotes are steadily off-centered with respect to each other. Thus the origin and evolution of central asymmetry could be different in these cases, which is not surprising given the totally different systems being studied.

### 4.2 Lopsidedness and bars in Mergers:

**1. Lopsidedness in centres of mergers:** The amplitude of  $m = 1$  indicates lopsidedness and is not affected by inclination effects (e.g., Rix & Zaritsky 1995). This is particularly important in the study of mergers where the disc plane may not be so well-defined in the central regions.

We note that the physical parameters  $A_1$ , the amplitude and  $p_1$ , the phase of lopsidedness show a different behaviour in mergers than that in the outer parts of normal galaxies. In the centres of mergers the amplitude  $A_1$  peaks at an intermediate radius of a few kpc and then decreases at larger radii (see Fig. 3), and the phase  $p_1$  shows large fluctuations with radius - see for example the results for Arp 221, Arp 224 and Arp 163 in Table 3. In contrast, in the outer parts (beyond  $\sim 1.5$  disc scalelengths or  $\sim 5$  kpc) of normal galaxies the  $A_1$  values show a steady increase with radius, and the phase  $p_1$  is nearly constant with radius - as seen from Rix & Zaritsky (1995), and Angiras et al. (2006). This constancy in phase indicates a global distortion (Jog 1997). Thus these two features clearly point to a different physical origin and evolution of lopsidedness in centres of mergers.

Our sample is chosen so that the two nuclei have coalesced to  $< 2''$  or the resolution of the data, or an average separation of  $< 500$  pc (see Table 2). The dynamical evolution of the central regions of mergers including the long lifetime of the central lopsidedness needs to be studied theoretically.

**2. Interpretation of  $A_2$  values:** The high values of  $A_2$  measured in the merger remnants here is unexpected, since a merger is expected to result in the disruption of a bar (Pfenniger 1991, Athanassoula & Bosma 1999). Also, these bars are stronger compared to the bars in normal galaxies (compare Table 2 in our paper with the Appendix in Bournaud et al. 2005 a).

It is interesting that in two of our sample galaxies which show a bar (Arp 160 and Arp 163), the outer regions are not relaxed and hence cannot be fit by either an  $r^{1/4}$  or an exponential profile, and yet the central region show a strong bar and lopsidedness. Thus the orbit building for the bars seems to proceed irrespective of the outer disturbed regions. The other galaxy showing a bar, Arp 162, is a class II galaxy which has a relaxed, exponential outer profile.

The high values of  $A_2$  measured in the other, non-barred galaxies could be due to an inclined thick disc, as discussed in Section 3.2. The class II galaxies are hybrid systems with

high random velocities and thick discs (Jog & Chitre 2002) and these have been shown to arise naturally in mergers of unequal-mass galaxies covering a range of 4.5:1-10:1 (Bournaud et al. 2004). The high values of  $A_2$  seen in the sample mergers of class II can thus be naturally explained as arising due to an inclined thick disc.

The values of  $A_2$  measured are higher for all class III galaxies. The high values of  $A_2$  if taken as an indication of an inclined thick disc- in no-fit galaxies, which do not have a bar (such as Arp 254 and AM 1025-433), indicates the existence of a galactic plane even if the outer regions are highly disturbed.

The high  $A_2$  values seen in Class I galaxies with elliptical-like profiles is even more surprising. The isophotal analysis shows that these do not show the pattern expected of a bar, and we have argued that this could be due to an inclined disc (Section 3.2), thus these seem to be unusual systems.

In any case, it is clear that the central asymmetries ( $m=1$  and  $m=2$ ) seen in class I remnants indicate that they are dynamically still far from being regular elliptical galaxies. This is extra evidence in addition to the other arguments such as the high gas content, extended tails and outer disturbed profiles, and different kinematics seen in mergers which have been used to show that merger remnants and ellipticals are not identical (e.g., Kormendy & Sanders 1992, Shier & Fisher 1998).

**3. Variation with mass ratios and epoch of mergers:** There is no discernible difference in the sloshing values or the  $A_2$  values for class I and II (see Table 2), while the  $A_1$  values are higher for class II galaxies. Thus the mass ratio of the progenitor or merging galaxies does not seem to significantly affect the degree of central non-axisymmetry in mergers at a later stage in its evolution, when the outer parts have relaxed into an elliptical-like (class I) or an exponential (class II) luminosity profile.

However, the stage of relaxation does seem to be a significant factor, because the class III galaxies, which are in early stages of relaxation do show higher amplitudes of sloshing and lopsidedness. The various galaxies can thus be arranged in a time sequence for variation of central asymmetry as follows: the normal or non-merger galaxies (lowest asymmetry), young merger remnants of  $< 1Gyr$  or class III mergers (highest asymmetry), evolved merger remnants of  $< 2Gyr$  with relaxed outer regions or class I and II mergers (higher asymmetry compared to normal galaxies but lower compared to the young remnants). The dynamical evolution of the non-axisymmetric amplitude and its relation to the relaxation of the outer regions, need to be studied by future N-body simulations.

#### 4.3 Sloshing values and Fourier amplitudes:

While both sloshing and the Fourier amplitudes represent asymmetry, they do not represent the same physical quantity. For example, a galaxy which has concentric isophotes and hence shows no sloshing could still have a non-axisymmetric mass distribution as in a bar or a spiral arm ( $m=2$ ). Thus the sloshing represents odd values of non-axisymmetric Fourier amplitudes. Indeed the typical sloshing and  $A_1$  values (see Figs. 2 and 3, or Table 2) are corre-

lated - although it must be kept in mind that the sloshing represents only the inner regions ( $< 1$  kpc) of a galaxy while the non-axisymmetric analysis is typically carried out over a larger radial range of up to 5 kpc or more.

On comparing with the values for the normal galaxies (Tables 2 and 4), we find that these have comparable values for sloshing (especially the class I and II mergers, and the normal galaxies sample), but the  $A_1$  values for the mergers are distinctly higher than for the normal galaxies.

## 5 SUMMARY

We have measured the non-axisymmetry in the mass distribution within the central few kpc of advanced mergers of galaxies which have merged into a single nucleus but have indications of interactions including tidal tails. The main results obtained are:

1. The mergers show strong non-axisymmetry - with the centres of isophotes showing a sloshing by  $\sim 20-30\%$  within the central 1 kpc. The asymmetry is also high, as measured by the Fourier amplitudes of the central light distribution. The typical fractional lopsided amplitude ( $A_1$ ) within the central 5 kps is found to be high  $\sim 0.12$  going upto 0.2, while the typical  $A_2$  values are higher  $\sim 0.2$  going upto 0.3. This implies the presence of bars as in Arp 160, Arp 162, and Arp 163 or thick discs as in the rest of the sample, both of which are unexpected in mergers with elliptical profiles or in no-fit, unrelaxed galaxies.

The corresponding values especially for the lopsidedness for a control sample of non-merger galaxies are smaller by a factor of 2-4, this confirms that the high central asymmetry in mergers discovered and measured in this paper can be truly attributed to the merger history.

2. The ratio of masses of galaxies undergoing the merger does not have a strong influence on the value of the central asymmetry once the outer regions have relaxed (Sections 1 and 4.2).

3. The stage of merger, however, does seem to be significant because the galaxies where the outer regions are non-relaxed, show a higher amplitude of asymmetry in the inner regions (Section 4.2).

4. The mergers are about 1-2 Gyr old as shown by the N-body simulations (Bournaud et al 2004). Thus in all cases studied, the central asymmetry appears to be long-lived, lasting for over 100 local dynamical timescales. This can be important for the dynamical evolution of the central regions of mergers.

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#### Appendix A: Notes on Individual Galaxies:

The details of sloshing as well as the non-axisymmetric Fourier amplitudes obtained for each galaxy in Section 3 are summarised below:

#### Class I galaxies:

1. Arp 221: The coordinates of the centre remain constant in the inner 4" and change beyond that. The non-axisymmetric analysis shows that the  $A_2$ ,  $A_3$  and  $A_4$  values are small while  $A_1$  shows a maximum of 0.25 at 8".
2. Arp 222: The coordinates of the centre remain constant in the inner 20" and change beyond that. This galaxy has very low  $A_1$  values.  $A_2$  maintains a constant value of 0.3 from the center to about 30". The  $A_3$  and  $A_4$  values are both very small.
3. Arp 225: The coordinates of the centre are constant in the inner 18". This galaxy shows low values of  $A_1$ ,  $A_3$  and  $A_4$  but high  $A_2$  values. The behaviour of  $A_2$  is similar to that seen in Arp 222.  $A_2$  maintains a value of 0.3 in the inner 45".
4. AM 0612-373: There is no substantial change in the coordinates of the center, with a total change of 1 pixel for  $x_0$  and  $y_0$ . The value of  $A_1$  is low, while  $A_2$  is quite high, peaking at 0.6 at 15". The  $A_3$  and  $A_4$  values are fairly high.

#### Class II galaxies:

5. Arp 162: The centre co-ordinates  $x_0$ , and  $y_0$  are constant in the inner 14". The values of  $A_1$  and  $A_3$  are extremely small. The amplitude  $A_2$  starts off at about 0.2 between 6"-20" and then increases to 0.3 beyond that, while  $A_4$  is low in the inner 20" and then increases. The phase angle is nearly constant throughout for the  $m=2$  and 4 components.
6. Arp 212: The centre co-ordinates  $x_0$ , and  $y_0$  remain constant in the inner 6" and then change substantially. All A coefficients show (nearly) double-peaked behaviour. The values of the A coefficients decrease in the order:  $A_1 > A_2 > A_3 > A_4$ .
7. Arp 224: The centre ( $x_0$ ,  $y_0$ ) remains constant in the inner 6". The value of  $A_1$  is high showing a peak of 0.3 at 12". In this case also,  $A_1 > A_2 > A_3 > A_4$ .

#### Class III galaxies:

8. Arp 160: This shows a constantly changing centre ( $x_0$ ,  $y_0$ ) for the subsequent isophotes. The values of  $A_2$  are also high with a peak of 0.45 at 10".
9. Arp 163: This also shows a constantly changing centre ( $x_0$  and  $y_0$ ) for the nearby isophotes. The value of the  $m=2$  amplitude  $A_2$  is the strongest, with a maximum of 0.4 between 10"-14". The value of  $A_1$  peaks at 0.3 at 6", and  $A_4$  peaks at 0.3 at 14". The value of  $A_3$  is small at all radii.
10. Arp 209: The centre co-ordinates are constant in the inner 4", and vary thereafter. The values of  $A_1$ ,  $A_2$  and  $A_3$  are high.
11. Arp 254: This shows changing co-ordinates for the centre. The values of  $A_2$  and  $A_4$  are large as compared to the values of  $A_1$  and  $A_3$ .
12. AM 1045-433: This is a Toomre sequence galaxy. Here the co-ordinates of the centre ( $x_0$  and  $y_0$ ) show a change from the innermost region itself. The value of  $A_2$  is high with a peak value of 0.5 at 20". This galaxy shows the following values for the Fourier amplitudes:  $A_2 > A_3 > A_4 > A_1$ .

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